Rapid, Safe Inspection of Water-spanning Infrastructure via Amphibious Unmanned Aerial Vehicle

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Abstract

As transportation infrastructure ages and is subjected to serious weather events, the improper, incomplete, or infrequent inspection of structures represents a serious threat to public safety both nationally and within the State of Louisiana. Besides the potential for serious injury, the repair costs associated with late discovery of problems can represent a substantial unplanned expense for transportation departments. This is especially true of critical but hard-to-reach areas such as the undersides of water-spanning structures as are common within the State. Thus, there is a pressing need for a technology that allows for rapid, safe, and thorough inspection of water-spanning infrastructure in a cost-effective manner. The **primary objective** of this research was to design, develop, deploy, and evaluate an amphibious unmanned aerial vehicle (UAV) system capable of shooting high-definition video and pictures from multiple viewpoints as part of infrastructure inspection activities for water-spanning infrastructure. A prototype was designed using sound engineering practices and its mechanical suitability simulated using 3D finite element analysis. Additive manufacturing in the form of 3D printing was utilized to create lightweight plastic body panels of complex, custom geometry. Upon final assembly, the prototype UAV passed basic functionality benchtop tests. However, the prototype was critically damaged during exterior flight testing and resulting issues could not be resolved by project's end.

IMPLEMENTATION STATEMENT

The ability to operate from water as well as land makes the envisioned solution especially attractive to the State of Louisiana. A UAV with this ability would provide a versatile, cost-effective means of performing multi-view infrastructure inspection of hard-to-reach areas within the State at a fraction of the cost of late discovery repairs. It would also allow inspections to be accomplished while reducing the need for traffic disruptions and minimizing injury risk to transportation workers and the public.

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1. Introduction

Unmanned aerial vehicles (UAVs) have grown significantly in sophistication and prominence over the last two decades. In many fields, UAVs now offer the ability to access remote locations, cover large areas of land, and deliver payloads with reduced cost and safety risk compared to manned flight. While the use of UAVs versus manned flight is not appropriate for all applications, these benefits have motivated significant multidisciplinary research and development efforts into new ways in which such aerial platforms can be leveraged. The PI is aware of only two previously published reports of public transportation organizations exploring the use of UAVs for infrastructure inspection [1, 2]. One of these preceding projects focused almost exclusively on automated image processing [1], while the other could only image the top and sides of bridges due to using a conventional bottom-mounted camera [2]. Neither system was capable of taking off from or landing on water. As a result, such existing systems necessitate a designated flat, dry staging area nearby. This poses a significant challenge for long-span infrastructure over water such as the Atchafalaya Basin Bridge or the Lake Pontchartrain Causeway, where establishing such a staging area would require lane closure/traffic disruption. With the type of the UAV that is the focus of this work, it would be able to take off from and land on water as well as dry surfaces, while also being able to image the underside of water-spanning infrastructure. This represents a suite of capabilities especially well suited to the State of Louisiana and other Gulf Coast States as well as a novel implementation of cutting-edge UAV technology. This work thus represents preliminary work on an untested/novel idea (amphibious UAVs for transportation support). More broadly, the project serves to demonstrate that transportation professionals within the State of Louisiana are leaders in technology adoption and innovation.

2. Objectives

This work had the **primary objective** of designing, developing, deploying, and evaluating an amphibious unmanned aerial vehicle (UAV, or drone) system capable of shooting high-definition video and pictures from multiple viewpoints as part of infrastructure inspection activities for water-spanning infrastructure. The ability to operate from water as well as land makes the solution especially attractive to the State of Louisiana. This project sought to provide a versatile, cost-effective means of performing multi-view infrastructure inspection of hard-to-reach areas within the State at a fraction of the cost of late discovery repairs. This would also allow inspections to be accomplished while reducing the need for traffic disruptions and minimizing injury risk to transportation workers and the public.

Secondary beneficial objectives included a) the publication and dissemination of findings related to this work for the wider benefit of transportation professionals including experimental data, proof-of-concept, and performance feedback, and b) the professional development of one supported graduate student and one supported undergraduate student towards advanced understanding of the specific challenges, priorities, and best practices associated with work in the field of transportation.

3. Scope

As a TIRE project of one-year duration, the scope of this project is limited to preliminary work and proof-of-concept. As such, the majority of the work focused on design and fabrication of the amphibious UAV, with aerial testing being limited to simple flights under very controlled conditions at Tech Farm – a rural open space owned by Louisiana Tech University which has been utilized for developmental UAV testing in recent years. Testing of in-flight inspection of actual water-spanning infrastructure was to be limited to decommissioned or rarely used locations as identified by DoT officials, should initial testing be successful.

4. Methodology

The first and perhaps most vital task accomplished on this project was the recruitment of talented and motivated students to perform the necessary design, fabrication, and testing activities. The recruited graduate assistant was Tithi Desai (**Figure 1a**), a Ph. D. in Engineering student whose background includes a Master's degree in Digital Electronics and Advanced Communication from Manipal University in Dubai. Besides her academic training, Tithi has prior experience with drone design. The added electronics complexity and multifaceted design elements compared to previous projects means that Tithi's skills were a great asset. For mechanical design tasks, Patrick Morgan, a talented mechanical engineering major, was recruited (**Figure 1b**). Patrick's skills include computer-aided design and simulation, materials selection, and fabrication techniques. These two supported students worked together, with Patrick leading the mechanical design and body assembly tasks while Tithi led the electronics system design and integration activities. The two students collaborated since project's inception, with the intent that both aspects be designed and tested in parallel and then integrated together into the final prototype.

Figure 1. The supported graduate student Tithi Desai (left) and undergraduate student Patrick Morgan (right).

5. Discussion of Results

At the project's inception, the work was organized into two phases with major tasks associated with each phase. These phases and tasks are itemized below with major results and accomplishments described.

<u>Phase I – Realization of the Amphibious UAV Prototype</u>

Task 1: Literature Review – The PI and his students reviewed both academic literature and current commercial UAV offerings in order to make the most educated design choices in terms of overall concept, component selection, and critical design elements. The vast majority of useful literature came from commercial sources regarding the current state-of-the-art in UAV technology and capabilities. **STATUS: COMPLETE**

Task 2: Engineering Design and Analysis – The team progressed from concept to detailed design via rigorous engineering analysis including determination of required lift, motor sizing, electrical power needs, buoyancy when afloat, mechanical strength/rigidity, and materials selection. An annotated computer model of the final concept is shown in **Figure 2**. The overall concept is a hexcopter design supported by a pair of pontoons which extend below the main body. An upward-facing camera with pan-and-tilt capability is mounted on the top of the main body and is protected from moisture via a transparent viewing dome. The main body also doubles as the electronics enclosure where flight controller, battery, electronic speed controllers, GPS, and video streaming hardware are located. The six arms of the drone are high strength, light weight carbon fiber tubing, while the top and bottom planar surfaces of the main body are carbon fiber sheet to be cut to specific shape and size. The main body is comprised of a high-strength PLA plastic that is compatible with additive manufacturing (also known as 3D printing), which allows for rapid prototyping and complex geometries. All seams are sealed inside of the drone using marine silicone, while the motors are rendered marine-compliant using established techniques outlined in marine motor literature.

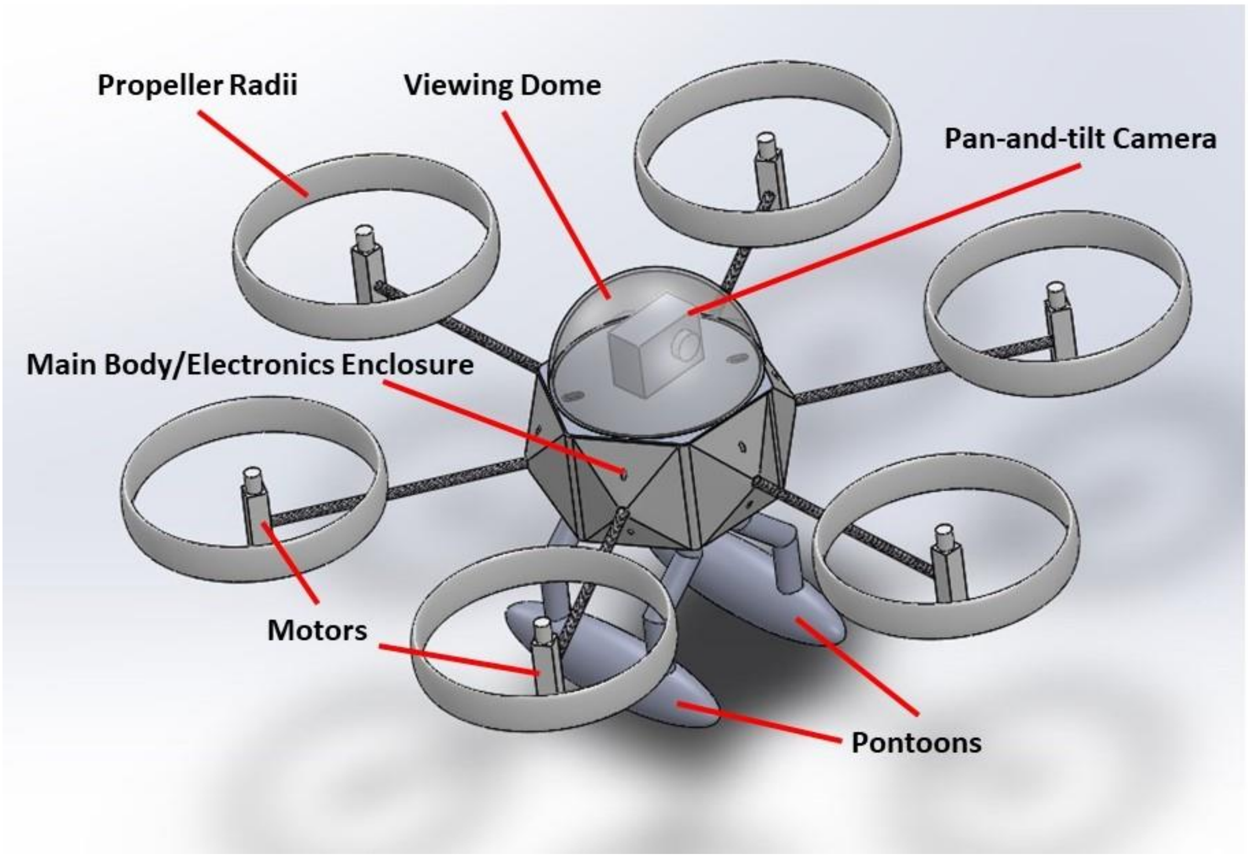

Figure 2. Annotated computer model of the assembled inspection drone.

Throughout the engineering design phase, finite element analysis (FEA) was performed to ensure that the drone was strong and rigid enough for stable flight while also minimizing weight/maximizing flight time. The design shown in Figure 2 meets these requirements, with a representative FEA simulation result shown in **Figure 3** below. In parallel to the mechanical design efforts, the electrical system was designed and components selected. This process was iterative, as the propeller/motor/battery/speed controller combination dictates the maximum force per motor, which drives the mechanical design. In addition, the total weight of the drone influences the number and size of motors used, which in turn affects the electrical design. At the end of the design phase, all electrical components had been identified including flight controller (3DR Pixhawk Mini), power subsystem (battery, power distribution board, motors, and speed controllers), and communication subsystem (control transceiver/receiver, video transmitter/receiver, GPS). **STATUS: COMPLETE**

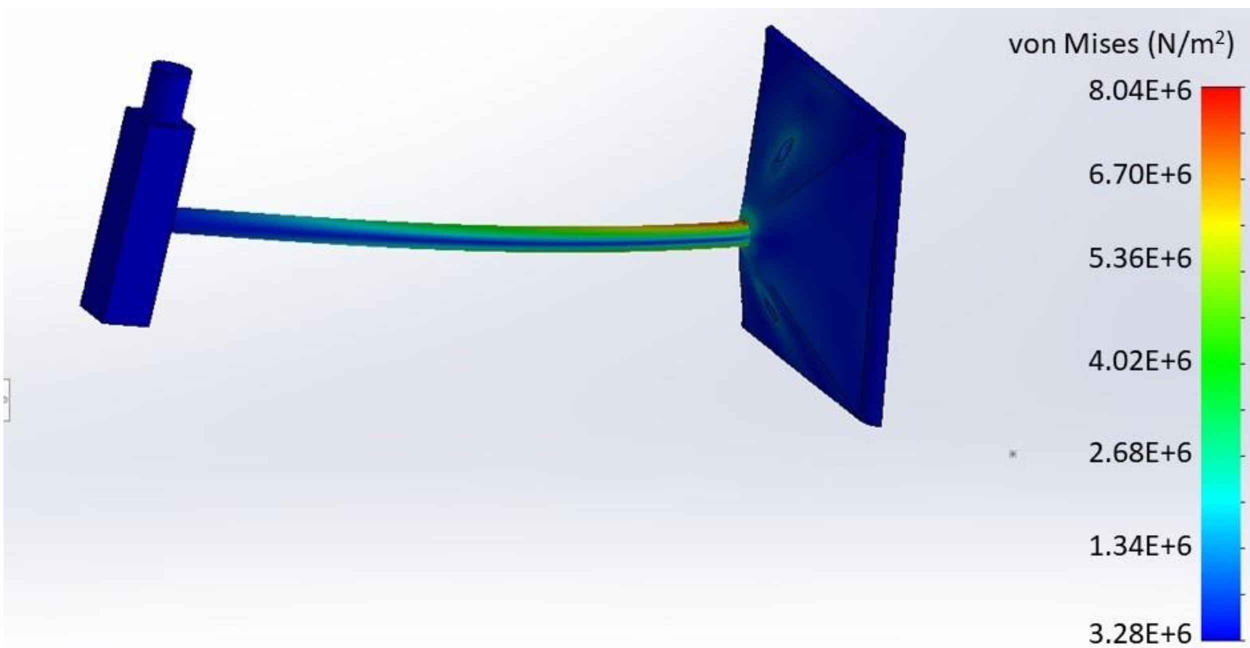

Figure 3. Finite element stress analysis of a single motor-arm-sidewall assembly in order to determine maximum stress magnitude and location.

Task 3: Fabrication and Systems Integration – As shown in **Figure 4**, the pyramid-shaped sidewalls were 3D printed and integrated with commercially-obtained graphite tubing to serve as the main structural elements. Graphite sheet was used for the top and bottom plates, with water jet cutting used to achieve hexagonal shapes with appropriate tabs to interface with the sidewalls. This same approach was also used to cut out mounting holes for the pan-and-tilt camera.

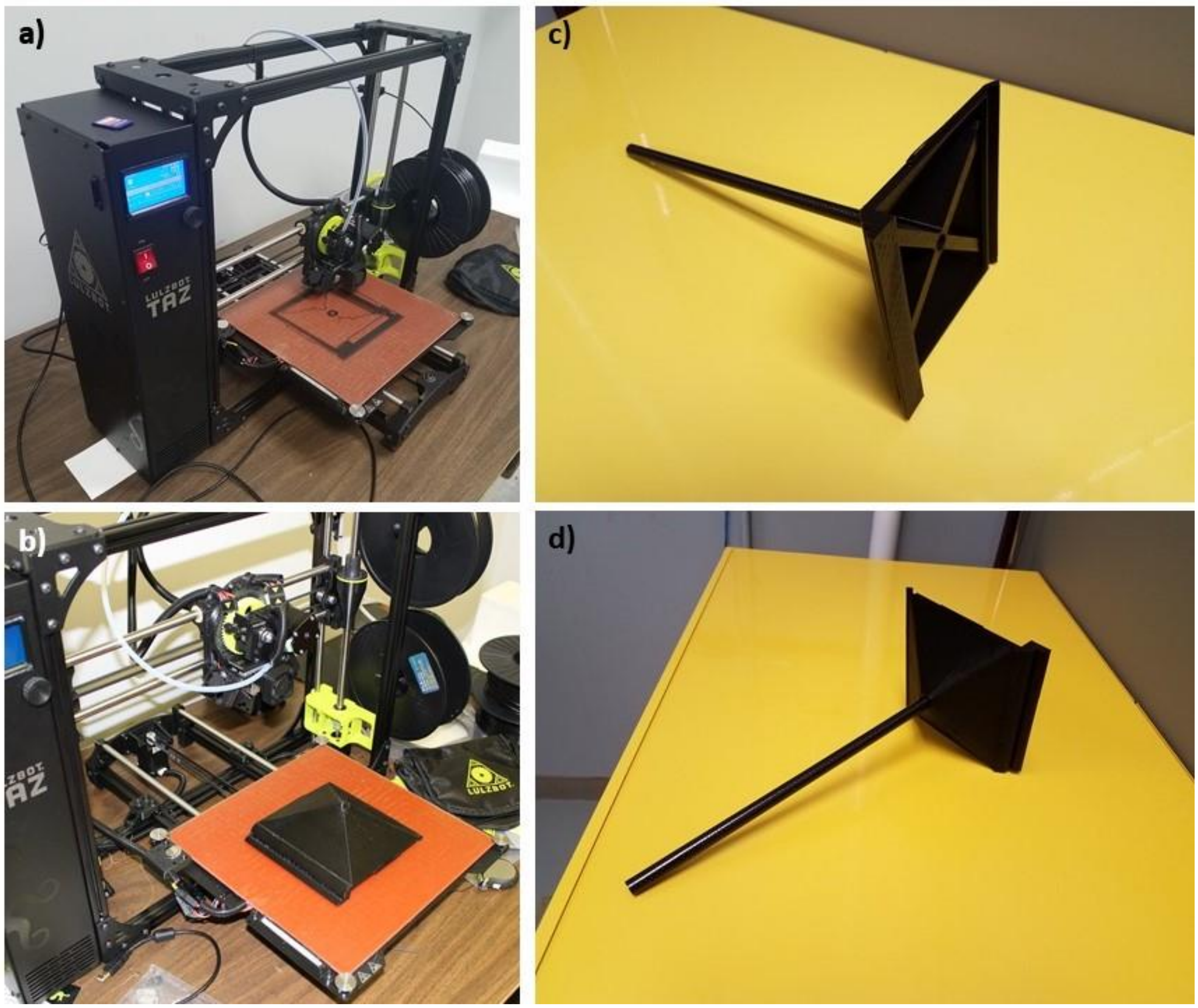

Figure 4. UAV body fabrication activities. a) A 3D print of one sidewall beginning. b) The completed sidewall. c) Inside view of the sidewall with graphite tube "arm" inserted. d) Outside view of the same sidewall/arm assembly.

In parallel to this work, the entirety of the electrical components was procured and successfully integrated together on a laboratory benchtop. This was achieved by mounting all six motors to a test board and completely wiring the system such that transceiver/receiver linking, motor control, video streaming, and GPS functionality could all be set up, debugged, and optimized independently of the mechanical aspects of the project. This benchtop setup is shown in **Figure 5**. Upon completion of the drone body, the electrical components were installed within the body with the same wiring scheme as implemented on the benchtop setup. Images of the completed drone are shown in **Figure 6** and **Figure 7**. **STATUS: COMPLETE**

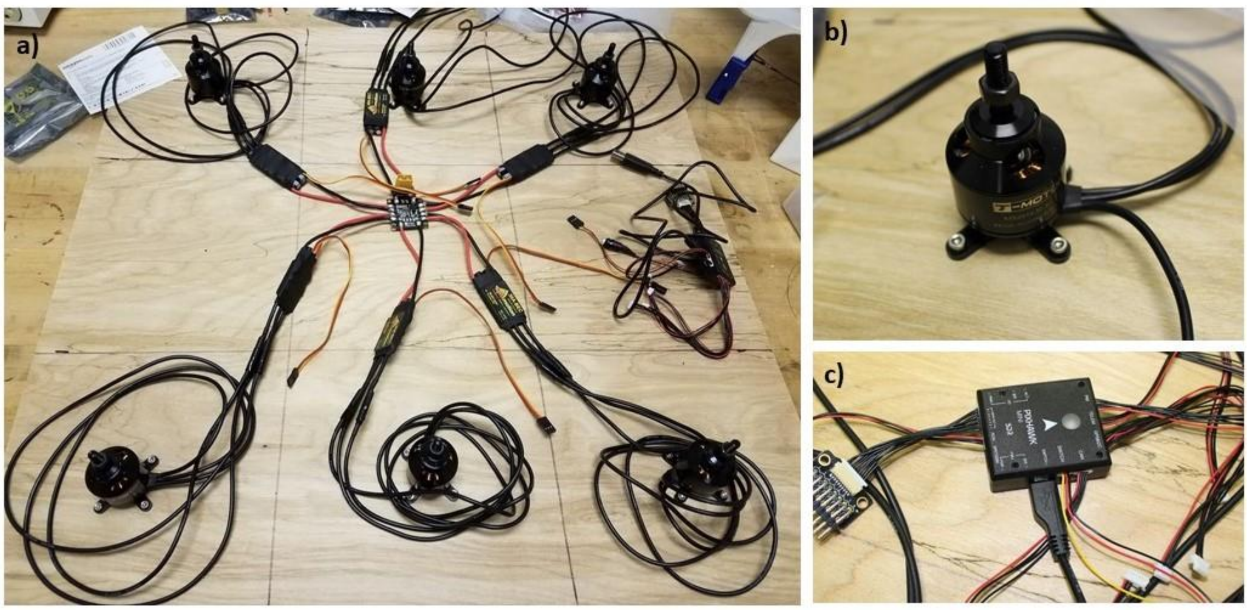

Figure 5. UAV electrical component wiring and integration activities. a) The six motors mounted to a benchtop integration setup along with electronic speed controllers and a power distribution board. b) A closeup of one of the six motors. c) The 3DR Pixhawk Mini flight controller, ready for programming via the USB uplink cable and associated laptop (not shown).

Figure 6. The fully assembled UAV prototype hexcopter.

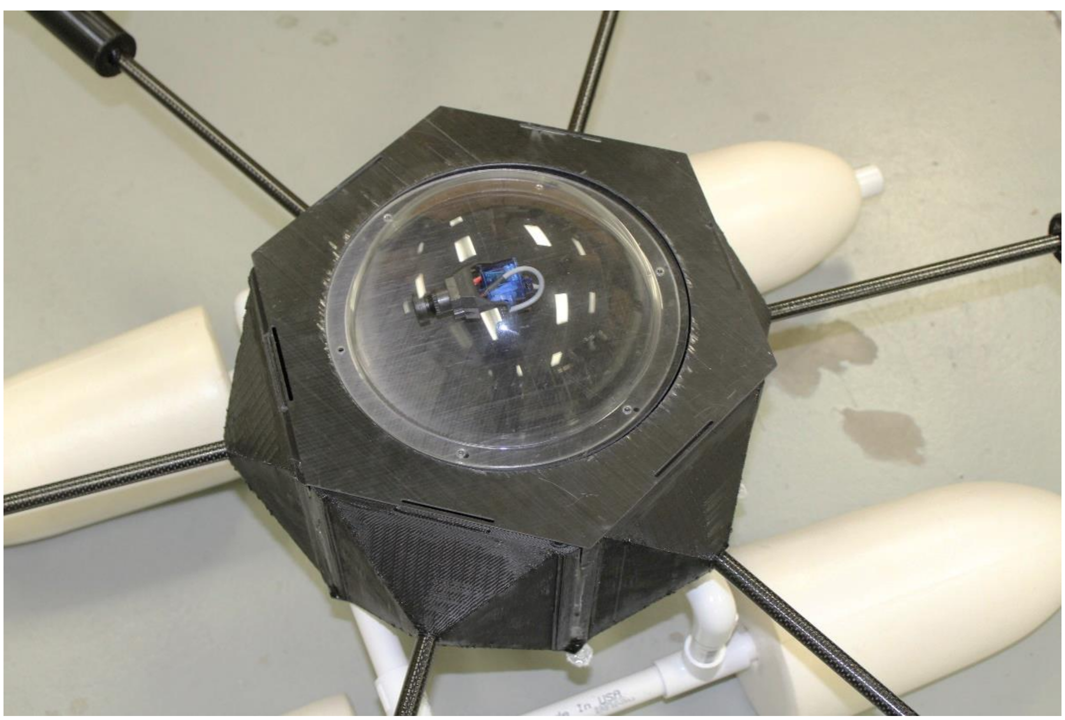

Figure 7. Close-up of the fully assembled UAV prototype hexcopter.

Phase II – Controlled Testing and Refinement

Task 4: Simple Flight Testing – The assembled amphibious UAV underwent simple flight testing at Tech Farm, a large open area owned by the University which has successfully been used as a testing ground for small developmental UAVs in recent years. This testing centered on verifying the airworthiness of the prototype as well as familiarizing the student pilot as to its handling. All flight activities were personally supervised by the PI, who possesses an FAA Remote Pilot License and is thus qualified under FAA Section 107 to serve as a Pilot in Command.

This is where the TIRE project ran into significant issues. First, there were significant communication issues between the transceiver (remote) and receiver for the UAV, which took multiple weeks to resolve with the help of Customer Support form the transceiver's manufacturer. Next, a persistent power issue was discovered that was caused by unreliable "bullet" connectors between the motors and the electronic speed controllers (ESCs) that was not an issue on the benchtop but was prone to cause issues when the UAV was moved for outdoor testing. Finally, the UAV was able to be fully powered and armed via the remote control and all propellers rotated as commanded. However, upon takeoff a flight controller software error occurred that caused two adjacent propellers to spin at slower speed than the remaining four. This resulted in the UAV flipping over and experiencing a hard landing, which broke one of the 3D-printed motor mounts completely. Repair efforts were not successful to a degree that would allow safe testing with the possibility of a motor/propeller being released (**Figure 8**), and 3D-printing a replacement could not be achieved before project's end-date. **STATUS: COMPLETE**

Figure 8. Close-up of the broken motor mount after a repair attempt was made. Fracture was across the two bolts holes on the right.

Task 5: Image Capture from Actual Infrastructure – This task could not be attempted due to the safety and time limitations outlined above. **STATUS: INCOMPLETE**

6. Conclusions

The design of an amphibious UAV for remote inspection of water-spanning infrastructure was undertaken, with the design itself being guided by sound engineering practices including finite element analysis. A prototype was designed and fabricated, with 3D printing playing a critical role in achieving complex, lightweight plastic components that would not be able to be achieved otherwise. Electronics integration was successful at the benchtop, but ran into a series of practical hurdles when integrated into the UAV body and during exterior flight testing. Finally, damage sustained during flight testing as well as general unreliability of control structures prevented safe testing of the drone further by project’s end.

7. Recommendations

It is the PI’s belief that the mechanical design and overall electrical design of the UAV are sound and would be successful with additional efforts. However, the flight controller and its associated software caused repeated problems including intermittent communication, unresponsive controls, and general unreliable behavior. The flight control scheme in use was chosen due to its ability to work well with GPS. However, since that time other GPS-ready flight controllers have been made available that may offer superior performance. If a similar project to this were to be of interest to LTRC, it is the PI’s recommendation that a different flight control strategy be implemented that takes advantage of further maturation of the technology than was available at this project’s inception.

8. References

[1] Z. Yin, Y. Mao, and C. Seto, "Develop a UAV Platform for Automated Bridge Inspection," Mid-America Transportation Center, University of Nebraska-Lincoln2015.

[2] J. Zink and B. Lovelace, "Unmanned Aerial Vehicle Bridge Inspection Demonstration Project," Minnesota Department of Transportation2015.